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Rates and Effects of Sedimentation in the Context of Dredging and Dredged Material Placement

PURPOSE: Dredging and disposal of dredged material in aquatic environments can expose animals and plants to episodic pulses of suspended sediment. Resuspended material can be deposited in thin layers adjacent to the dredging or disposal areas in some cases as much as several thousand meters distant (LaSalle et al. 1991). While our understanding of the potential effects of such far-field deposition is limited, some estuarine organisms may be highly sensitive to suspended sediments and certain life stages (eggs, juveniles) may be particularly affected by resuspension and deposition. In this report potential impacts of sedimentation (bedded materials) are reviewed with emphasis on those habitats believed to be most sensitive.

BACKGROUND: Ambient conditions for estuarine organisms are rarely static, and most organisms are adapted to varying concentrations of suspended sediment (see bibliography in Kerr (1995)). The intensity and duration of resuspension from dredging and disposal operations is highly dependent on the type of equipment, operator, character of sediment, and local hydrodynamic conditions (Collins 1995; Clarke and Wilber 2000). While the effects of elevated concentrations of total suspended solids (TSS) and thin layers of sediment on estuarine organisms are poorly understood (Wilber and Clarke 2001, Wilber et al. in preparation), we do know that some of the defining characteristics of an estuarine environment are highly variable conditions in the water column for temperature, salinity, and particulate flux.

The direct measurement of TSS is straightforward and can be complemented with indirect optical and acoustic measurements (optical backscatter sensors, transmissivity, acoustic doppler profiling) to achieve rapid characterization of large volumes of water over relevant spatial scales (Lohrman and Huhta 1994, Tubman et al. 1994, Land and Bray 1998, Puckette 1998, Tubman and Corson 2000, Reine et al. 2002). Understanding of the effects of TSS on salmonids and a limited number of non-salmonid estuarine fish and shellfish is sufficient to provide quantitative guidance on acceptable levels of TSS under well-studied circumstances for a few animals. Although further research is required on dose-response curves of estuarine fish and early life stages, the technology to conduct these studies is well established (Wilber and Clarke 2001; Berry et al. 2003); dredging-induced TSS and their associated effects have been studied since the Army Corps' DMRP initiative in the 1970's. There are also well-established protocols for bioeffects testing for TSS impacts (U.S. Environmental Protection Agency and U.S. Army Corps of Engineers 1991, Caux et al. 1997); unfortunately, no such protocols exist for assessing sedimentation effects.

The measurement and assessment of effects of thick layers of sediment deposition (>1 cm) is advanced and well within the capabilities of existing technologies (e.g., Sediment Profile Imagery). It is far more difficult to reliably measure thin layers of sediment deposition from episodic events, although some promising techniques have been developed (Thomas and Ridd

2004). Because ambient sediment deposition and resuspension may be of the same order of magnitude as that induced by dredging or disposal, it is particularly difficult to isolate and quantify anthropogenic contributions to sedimentation. However, persistent concerns regarding the impacts of deposition of sediments from dredging or disposal activities on habitats, sessile shellfish and early life stages of fish require an evaluation of existing or emerging technologies for quantification of sediment deposition. Sediment deposition is also referred to as bedded sediment and is the primary focus of this assessment, as distinct from effects of suspended sediments.

METHODS: In order to understand potential effects of dredging-induced sedimentation, it is essential to define the critical range of parameters of concern (spatial, volume, temporal scales). To assist this process a panel of experts in sedimentation measurement and biological impacts was asked to define existing knowledge of scales of concern for biological response to sediment deposition, methods of assessing impact, requirements and limitations of existing predictive models, and state-of-the-art methods of measuring deposition in laboratory and field experiments.

The following scientists participated in the survey:

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The expert panel's responses are briefly synthesized in this technical note and more fully reported in Germano and Carey (in preparation). It should be noted at the onset that this synthesis focuses on sedimentation (bedded sediments) rather than suspended load per se. It is recognized that sediments are not likely to become bedded without having first contributed something to the suspended load, but the intent here to is to evaluate the effects of sediment after it has settled to the seafloor.

Predicting Impacts

Ranges of ambient sedimentation rates (instantaneous and cumulative) in habitats of concern. Ambient sedimentation rates in habitats of concern are not well known and appear highly dependent on events and specific environmental conditions. However, to provide boundary conditions for field and laboratory measurements to detect change resulting from anthropogenic effects it is necessary to determine at least a range of ambient rates. Sedimentation rate is usually defined as the linear accumulation of sediment in centimeters per year ($cm\ yr^{-1}$) and may be converted into volumetric estimates of sediment flux, or mass accumulation rate (MAR), usually given in grams per square centimeter per year ($g\ cm^{-2}yr^{-1}$).

However, effects ranges are usually expressed in responses to total suspended solids or particulate concentrations (mg L^{-1}). It is clear that for some taxa of concern, the thickness of sediment accumulation may be critical and accumulation is not the same as water column concentration (see below). It is also important to understand the range and timing of natural sedimentation events in each region or habitat. An additional confounding factor for spawning grounds is that most monitoring programs and water quality regulations for streams are expressed in turbidity (often with a narrative description, e.g., cloudy, free from color or turbidity, reduced light transmission), which may be used as a surrogate for suspended sediment concentration or siltation (Gray and Glysson 2003).

An initial estimation of ambient sedimentation rates derived from published sources is presented in Table 1.

Table 1 Ambient Sedimentation Rates Derived from Published Sources		
Habitat	Sedimentation Rate	Concentration Near Bottom
Spawning grounds (for attached eggs, gravel, sand)	Unavailable	0.1-100 mg L^{-1}
Estuarine SAV	0.1-0.3 cm yr^{-1}	10-100 mg L^{-1}
Turbid estuaries – Fluid muds	0.3- 1.0 cm yr^{-1}	100 – 20000 mg L^{-1}

Minimum levels of sedimentation known to have an adverse impact on early life stages of fish. Available data on sedimentation expressed as concentration in the water column (potential sedimentation) do not appear to be sufficient to provide prediction of impacts on early life stages of fish. There is a need to determine relevant scales of sediment thickness and bulk characteristics prior to larval or egg settlement and deposition of sediment after attachment or settlement. The effects of increased sedimentation resulting in "embeddedness" (fine sediment filling in gaps between gravel in streams) on hatching of salmonid eggs has been described (Waters 1995) and has resulted in guidelines based on percent fines and other variables (Lotspeich and Everest 1981, Caux et al. 1997).

In the Great Lakes, Walleye (*Stizostiderm vitreum*) eggs and larvae also appear to be affected by sedimentation, but laboratory dose-response data are unavailable (D. Clarke 2004, http://www.glc.org/dredging/scoop/DougClarke.pdf). A small number of direct observations and studies indicate that attachment of non-salmonid fish eggs to benthic substrata can be inhibited by siltation. Pacific herring eggs appear to require virtual absence of fine sediment layers to allow attachment to the substratum (Stacey and Hourston 1982, Haegele and Schweigert 1985, Barnhart 1988). Winter flounder eggs were observed to be affected by thin layers of deposited sediments in laboratory conditions.[1]

Additional related information is available on the effects of both sediment transport and suspended sediment concentrations on the early life stages of fish. Lisle and Lewis (1992) provide a useful model of salmonid embryo survival based on streamflow and sediment transport. They were able to incorporate long-term streamflow records (6 years), bedload

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[1] Personal Communication. 2004. D. Nelson, National Marine Fisheries Service, Milford, CN.

transport, a relationship between transport and infiltration of bedload and fine sediment into gravel and the result of embryo survival and gravel properties. The results of their modeling effort indicated that further research was needed to clarify how sediment transport affects the intergravel environment and in turn the potential for embryo survival. Their approach is not directly transferable to estuarine environments but might provide some framework for assessment of impacts of sediment transport in spawning areas.

Relatively high suspended sediment concentrations (>500 mg L^{-1}) are known to have impacts on early life stages of estuarine fish (Wilber and Clarke 2001, Berry et al. 2003). However, the duration of exposure to suspended sediment from dredging or disposal must be related to the type and residence time of eggs or larvae in an affected habitat. Morgan and Levings (1989) demonstrated that after settlement, development of Pacific herring larvae is delayed at very high levels of suspended sediment (10,000 mg L^{-1}). But Boehlert and Morgan (1985) reported that feeding rates of larval Pacific herring increased with increasing turbidity up to a point when feeding was inhibited (2000 mg L^{-1}). Longer-term effects of sediment deposition are highly dependent on timing of egg attachment and larval settlement, which may be quite specific for a given habitat.

Minimum levels of sedimentation known to impact early life stages of shellfish. Similar to fish, the early life stages of shellfish can be affected by passage through high concentrations of suspended sediment in the water column, but eventually shellfish must either attach to a hard substratum or burrow into appropriate sediments. Bivalve larvae appear to tolerate relatively high suspended sediment concentrations (up to 400-800 mg L^{-1} for oyster larvae and up to 2200 mg L^{-1} for quahog larvae for less than two days, Wilber and Clarke 2001). Oyster larvae require a clean, hard substratum for attachment, but can tolerate thin layers of deposited sediments, perhaps up to 1 mm.[1] After attachment, oyster larvae can tolerate deposition of 2-3 mm, with 3-5 mm and above likely to have some negative effects.[1] Clam larvae are not likely to be affected by sediment deposited before settlement (except for potential effects on "selection" of settlement sites by larvae), but at the earliest stages, the newly settled larvae may not tolerate rapid deposition of fine sediments. Deposition rate and thickness would have to exceed the burrowing rate of the larval clams to have a negative impact. Suspended sediment and resuspended sediment (for attached or burrowing post-larvae) can affect the feeding and growth of bivalves (both larval and adult), and frequent or sustained exposure to high suspended sediment loads is clearly detrimental to most species. Field or laboratory measurements should account for stressors associated with high suspended load (including associated contaminants, ammonia, and sulfides).

Minimum levels of sedimentation known to have an adverse impact on submerged aquatic vegetation (SAV). Most assessments of loss of aquatic macrophytes have focused on impacts of changes in underwater light from increased suspended sediment (e.g., Best et al. (2001, Dennison et al. (1993). Accumulation of sediment may result in different responses among species of SAV and, in turn, different effects on sediment entrainment around SAV (Fonseca and Fisher 1986). Assessments along gradients of siltation in Southeast Asia have shown loss of species and changes in species composition, supporting the potential for differential responses among species

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[1] Personal Communication. 2004. Roger Mann, Professor, Virginia Institute of Marine Science, Glouchester Point, VA.

(Terrados et al. 1998). Effects of deposition may also be difficult to separate from associated effects of increased sediment flux including light attenuation (Terrados et al. 1998). Unfortunately, field assessments of effects of siltation or deposition on SAV in U.S. waters is very limited.

Successful settlement of kelp and other algal species on hard bottom substrata is clearly inhibited by very thin layers of sediment (0.008 mm). *Fucus serratus* embryos responded negatively to thicker layers of sediment, with a stronger negative reaction to fine and organically enriched sediments, and most strongly to the presence of sulfide (Chapman and Fletcher 2002).

Because SAV may have a very wide range of growth forms, sizes and phenotypic plasticity, the effects of deposition could vary considerably depending on habitat, season, and water depth. Deposition may affect growth and survival due to light limitation, accumulation of waste products due to limited diffusion and sulfide poisoning depending on grain size, water content, and organic content of sediments.

Methods for expressing levels of sedimentation (thickness, volume, dry/wt weight). Measurements of sedimentation (i.e., bedded sediments) relevant to biological effects may require several dimensional variables including thickness, density, percent fines, geometric mean size, and Fredle number (Caux et al. 1997). Fredle number is an index of permeability that has been correlated with survival to emergence of salmon and trout (Lotspeich and Everest 1981). Hinchey et al. (in preparation) chose effective overburden stress (kPa: bulk density and depth of burial as described in Richards et al. (1974) as a reliable measure of the force exerted on organisms by sediment burial, because it combines burial thickness and porosity. Their experiments with sediments from the Chesapeake Bay and York River were conducted to assess survival at 6 days of burial for a range of overburden thickness (0-25 cm) representing overburden stress from 0-16 kPa (Figure 1). Force may be most important to mobile organisms attempting to escape from deposition events, but permeability may be more important to the survival and growth of sessile organisms buried under very thin layers of sediment (<2 mm).
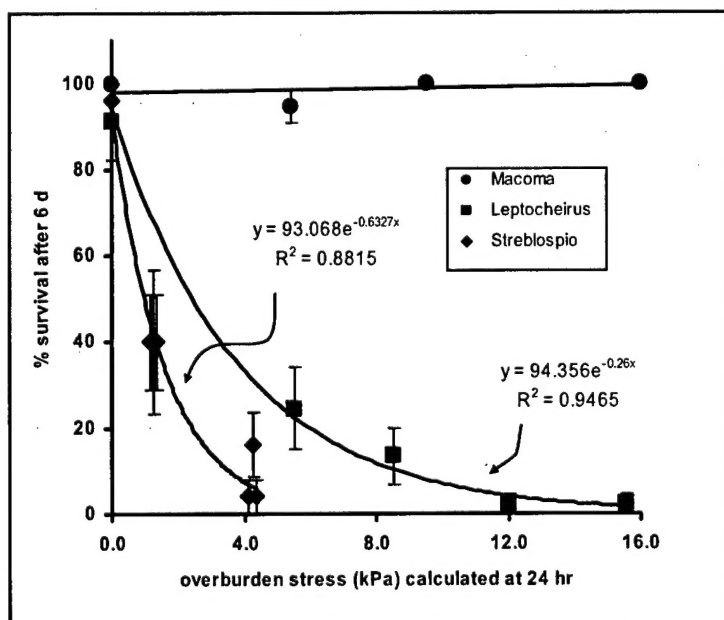

Figure 1. Percent survival of three benthic invertebrates to increasing overburden stress after 6 days of burial (from Hinchey et al., in preparation)

It appears that the consensus is that a combination of mass and some form of bulk density may be the most widely useful characterizations, but that grain size and permeability may have important implications. Even the apparently simplest variable, thickness, may be quite difficult to measure in situ (see below) at the lower end of the ambient range (0.1-0.3 cm).

Temporal scales of concern for impacts from sedimentation. Temporal scales of concern can be seen at several levels: duration of external event (days), timing of external events (seasons), persistence of the effects of external events (weeks). Taking each in turn, we can provide some boundaries for field and laboratory investigations. Duration of external event: assuming that sedimentation results from dredging or disposal events, dredging operations would likely move past an area of potential impact in 1-5 days, disposal operations would potentially last longer with episodic plumes or density currents depositing fresh layers of sediment. The former would approximate the duration of storm-induced disturbance, whereas the latter might approach chronic, recurring frequency during one or more seasons. Timing of external events: the scale of concern for timing of external events is closely related to the key seasonal events of reproduction and critical life stages or presence of organisms in the vicinity of the event(s). Persistence of effects of external events: in most sediment systems, newly settled sediment is subjected to biological and physical mixing to a degree immediately after placement. How quickly bedded sediments are incorporated into ambient sediments or re-transported is highly dependent on hydrodynamics and the ambient biological community. In some habitats, the introduction of fine sediments (for example, into coarse sands or gravel) might induce settlement and colonization of new populations altering the community and potentially further affecting species of concern or mediating the effects of the sedimentation events. Regardless, the time constant for assimilation of bedded sediments into some level of equilibrium is likely to be on the order of weeks. If silts become "embedded" into coarse sands or gravels, they may become resistant to erosion (it is harder to resuspend a fine cohesive particle [consolidated] than a larger grain size noncohesive particle).

Minimum length scale for time of sediment accumulation. The intent of this question was to understand what might be the shortest (most ephemeral) sedimentation event of concern. Based on responses received, events of hours or days could create impacts, but assessment of impacts should consider periods longer than one day (suggested time is 3-5 days).

Most sensitive biological resources to evaluate. It is important to note that eggs and larvae of estuarine and marine species typically suffer very high natural mortalities. While preventable sources of mortality are not welcome or meaningless, they must be of sufficient scale to have a measurable effect on population size or locally significant recruitment to overcome costs or effects of prevention. Assessing effects on population size will likely require modeling rather than observation. The following refined list focuses on direct effects of bedded sediments, recognizing that water column effects are also significant but outside the scope of this report.

- Eggs of benthic fishes that fail to attach, grow, or hatch. This may be the most sensitive resource, and it would be a very high priority if sedimentation at a site had the potential to cause the loss of an entire year class.

- Non-burrowing substrate organisms, SAV, shell reefs (oysters). This may not be most sensitive (with the exception of some kelp), but loss or impairment (growth, reproduction) would require long recovery time (long-lived, difficult to establish stable population).
- Eggs and larvae of pelagic fish if near bottom. Many pelagic fish have eggs or early life stages that settle to the bottom and may be affected by bedded sediment.
- Avoidance or failure of spawning by adults due to sudden presence of sediments. This response has the potential to be deleterious to a population, but unless the species has a very high site affinity or disturbance is very widespread, it will be difficult to assess whether adults successfully spawn elsewhere. May be amenable to modeling.
- Metamorphosis of benthic life stages of fish. Little is known of the effects of sediment on this process, but it has the potential to affect a critical life stage.
- Juvenile fish. Both pelagic and benthic fish are likely to be vulnerable to predation and/or restriction of food supply if they avoid areas due to sedimentation.
- Sessile benthic invertebrates. The most sensitive would include non-burrowing filter feeders (apart from shell reefs above) followed by interface feeders.
- Benthic fish. Benthic fish can have high affinity to specific substrate types but are also capable of relocating during the assimilation of the bedded sediments. Relocation may subject fish to increased predation or loss of foraging area.
- Burrowing benthic invertebrates. Relatively high overburden stress would be required to affect burrowing invertebrates, but this may scale with the size of the organism.
- Pelagic fish. Pelagic fish are least likely to be sensitive to bedded sediments, but may react to effects on food resources.

Evaluation of Impacts

Appropriate laboratory time scales for measuring impact of sedimentation on fish/shellfish/SAV. Laboratory time scales should reflect assumptions of field effects; duration of event, 3-5 days; assessment of impacts:
- Adhesion of eggs (e.g., herring) in the presence of varying concentrations of sediments.
- Fertilization success of eggs in presence of sediments.
- Developmental success and hatching (days to weeks).
- Larval behavior and feeding: minutes to hours.
- Development of kelp: hours to days.
- Long-term effects on adults: SAV growth and physiology-hours to weeks.

Appropriate laboratory volume scales for measuring impact of sedimentation on fish/shellfish/SAV. This will depend on scale of organism and mass or volume of bedded layer. Based on species and life stages of concern, benthic fish eggs and larvae are a high priority and may be most tractable based on scale. Eggs and embryos can be on the milliliter scale (see Chapman and Fletcher (2002)), whereas larvae and juveniles may require many liters to even mesocosm scales. Complexity of scaling effects becomes more difficult as the size of the organism increases.

Appropriate in-situ time scales for measuring impact of sedimentation on fish/shellfish/SAV. Short-term measurements are most likely to capture direct effects of sedimentation events, and should extend from hours to 3-5 days. Longer-term measurements are

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likely to be confounded by natural resuspension and settlement events, but might detect more subtle impacts if paired with adequate controls. Longer-term experiments might require an entire recruitment to grow out with a cycle of months to years.

Appropriate in situ volume scales for measuring impact of sedimentation on fish/shellfish/SAV. Evaluate the initial mixing zone and extent of any density flows adjacent to the dredging or disposal event(s). Spatial extent of measurable sedimentation could range from 200-1,000 m away from source, but strongest effects will occur less than 300 m from the source.

Requirements and Limitations of Predictive Models

Resuspension or sedimentation input data needed for validation of models. The characteristics of resuspension are explicitly provided to all currently operational models (both the loss rates as well as the production rates are input variables), but there are no models of resuspension per se unless one considers empirical algorithms as models. However, additional field data providing a direct measure of suspended material concentrations at various points over the vertical dimension and at various distances downstream of the operating dredge are always of value. The increasing use of acoustic techniques should improve three-dimensional (3-D) understanding of plume structure; if the detail over the vertical is considered, an agreement on the character of the plume resulting from both hydraulic and mechanical dredging operations may finally be reached. The achievement of this goal requires close collaboration between scientists/engineers and dredge operators.

The variety of models detailing sedimentation of materials placed in suspension by dredging would benefit from direct measures of the resulting deposit characteristics (3-D measurements) following completion of dredging. This might be best realized by high-resolution measurements of short-lived radionuclides (e.g., ^{7}Be) from diver-placed cores obtained before and after dredging at selected points along and across mapped plume trajectory. In some cases, these measurements could be complemented by sediment profile camera data. These latter observations might only work if placement of the camera was very accurately controlled (staked locations, diver deployed) and the thickness of deposition was in excess of ~0.5 cm. The latter criteria suggest that measurements would be best used in the initial mixing zone – the area characterized by an exponential decrease in suspended material concentration with distance.

Limiting factors in existing models. All models are less than perfect in handling settling velocities. Because gravitational settling is the primary process driving the resuspended materials to the bottom, this parameter must be accurately defined. Most of the models struggle with this to a greater or lesser degree. Work is in progress but more needs to be done.

All of the existing models considered (TASS, SSFATE, STFATE, and DREDGE) are fundamentally advection/diffusion formulations dealing with the dispersion of sediments emanating from a source. The sediments are carried by the local flows and settle to the bed. Once on the bottom they stay in place. There is no consideration of subsequent resuspension and transport and/or mixing with ambient sediments. This is a major deficiency. Freshly deposited sediments are subject to nearly immediate resuspension and mixing with the ambient suspended material field. Such mixing has the potential to significantly reduce the effect of the newly

introduced sediments on the benthic community. It also may serve to complicate the establishment of cause-and-effect relationships. A model that provides a means to quantify the extent and timing of mixing along the sediment-water interface should be considered an element essential to any effort to quantitatively define the biological impacts of dredge-induced sedimentation.

Another type of available model is the dynamic energy budget (DEB) individual-based model (Noonburg et al. 1998, Nisbet et al. 2000) to predict effects of stress on organism growth and survival. These models need detailed lab data for input (growth, respiration, survival) in response to sediment exposure. They are very useful for specific predictions of impacts and how to link these individual effects to population responses. However, these require detailed laboratory results on response of specific organisms to bedded sediments.

CONCLUSIONS AND RECOMMENDATIONS: Of the biological resources of concern listed earlier (SAV, commercial shellfish beds, fish, and spawning areas), the first two are very amenable to conventional monitoring techniques to assess physiological responses of the organisms because they are stationary. For monitoring the response of fish to sedimentation events in the field, the available techniques would vary with the location and scale of the sedimentation event. Once that is known, monitoring the behavioral responses of fish would be most instructive. Current tagging technologies provide a number of possibilities for both juvenile and adult fishes in order to measure behavioral responses.

Monitoring the effects/responses to spawning areas would be much more complicated; possibilities exist for monitoring both gamete/larvae reactions as well as adult spawning behavior through the use of quantitative motion analysis (Dutta et al. 1989, Gerlich et al. 2003). While this offers the potential for addressing the effects of suspended sediment particles on swimming speeds, velocity, and orientation of either adults or gametes, it is more amenable to laboratory studies rather than field monitoring efforts. Some new emerging technologies using motion analysis are being developed in the medical diagnostic field (wearable accelerometric dataloggers) for assessing movement disorders (Sabelman et al. in preparation). While these new technologies hold potential for studying adult fish movements, it will be some time before they will be affordable or could be adapted for aquatic organisms in either laboratory or field studies.

Because knowing the "scale at which the problem exists" is a first-order question, priorities for the short term would be to invest in appropriate instrumentation to determine both ambient and dredging-induced sedimentation rates. Field trials at a number of different field sites with different types of dredging operations (e.g., clamshell, cutterhead, and trailer suction dredge) should be performed to determine the area of seafloor affected by sediment accumulation, the vertical height of these accumulated layers, and the timescale over which these accumulations develop. Once definite data are acquired regarding the scale of sedimentation, biological impacts could be more effectively assessed.

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> Germano, J. D., and Cary, D. (2005). "Rates and effects of sedimentation in the context of dredging and dredged material placement," _DOER Technical Notes Collection_ (ERDC TN-DOER-Ex), U.S. Army Engineer Research and Development Center, Vicksburg, MS. _http://el.erdc.usace.army.mil/dots/doer/doer.html_

REFERENCES

Barnhart, R. A. (1988). "Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates-Pacific herring," U.S. Fish and Wildlife Service Biological Report 82 (11.79), Technical Report EL-82-4, U.S. Army Engineer Waterways Experiment Station, Vicksubrg, MS.

Berry, W., Rubenstein, N., Melzian, B. and Hill, B. (2003). "The biological effects of suspended and bedded sediments (SABS) in Aquatic Systems: A review," Internal report to USEPA, Office of Research and Development, National Health and Environmental Effects Laboratory, Narragansett, RI.

Best, E. P. H., Buzzelli, C. P., Bartell, S. M., Wetzel, R. L., Boyd, W. A., Doyle, R. D. and Campbell, K. R. (2001). "Modeling submersed macrophyte growth in relation to underwater light climate: Modeling approaches and application potential," _Hydrobiologia_ 444, 43-70.

Boehlert, G. W., and Morgan, J. B. (1985). "Turbidity enhances feeding abilities of larval Pacific herring, _Clupea harengus pallasi_," _Hydrobiologia_ 123, 161-170.

Caux, P. -Y., Moore, D. R. J., and MacDonald, D. (1997). "Ambient water quality guidelines (criteria) for turbidity, suspended and benthic sediments," Technical Appendix. Prepared for British Columbia Ministry of Environment, Land and Parks, April 1997.

Chapman, A. S., and Fletcher, R. L. (2002). "Differential effects of sediments on survival and growth of _Fucus serratus_ embryos," _Journal of Phycology_ 38, 894-903.

Clarke, D. G., and Wilber, D. H. (2000). "Assessment of potential impacts of dredging operations due to sediment resuspension," _DOER Technical Notes Collection_ (ERDC TN-DOER-E9), U. S. Army Engineer Research and Development Center, Vicksburg, MS. _http://el.erdc.usace.army.mil/dots/doer/doer.html_

Collins, M. A. (1995). "Dredging-induced near-field resuspended sediment concentrations and source strengths," Miscellaneous Paper D-95-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dennison, W. C., Orth, R. J., Moore, K. A., Stevenson, J. C., Carter, V., Kollar, S., Bergstrom, P. W., and Batiuk, R. A. (1993). "Assessing water quality with submersed aquatic vegetation habitat requirements as barometers of Chesapeake Bay health," _Bioscience_ 43, 86-94.

Dutta, R., Manmatha, R., Williams, L. R., and Riseman, E. M. (1989). "A data set for quantitative motion analysis," _Proceedings of a Workshop on Image Understanding_. Morgan Kaufmann Publishers, Inc., Palo Alto, CA, 714-720.

Fonseca, M.S., and Fisher, J. S. (1986). "A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration," _Marine Ecology Progress Series_ 29, 15-22.

Gerlich, D., Mattes, J. and Eils, R. (2003). "Quantitative motion analysis and visualization of cellular structures," _Methods_ 29, 3-13.

Germano, J. D., and Cary, D. (2004). "Potential methods for direct measurement of sedimentation in estuarine and marine environments," in preparation, U. S. Army Engineer Research and Development Center, Vicksburg, MS.

Gray, J. R., and Glysson, G. D. (2003). "Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates," *U. S. Geological Survey Circular 1250,* http://water.usgs.gov/osw/techniques/turbidity.html (June 30, 2003).

Haegele, C. W., and Schweigert, J. F. (1985). "Estimation of egg numbers in Pacific herring spawns on giant kelp," *North American Journal of Fisheries Management* 5, 65-71.

Hinchey, E. K., Schaffner, L. C, Hoar, C. C., Vogt, B. W., and Batte, L. P. "Responses of estuarine benthic invertebrates to sediment burial: the importance of mobility and lifestyle," in preparation.

Kerr, S. J. (1995). "Silt, turbidity, and suspended sediments in the aquatic environment: An annotated bibliography and literature review," Technical Report TR-008, Ontario Ministry of Natural Resources, Southern Region Science and Technology Transfer Unit, Brockville, Ontario.

Land, J. M., and Bray, R. N. (1998). "Acoustic measurement of suspended solids for monitoring of dredging and dredged material disposal." *Proceedings, 15th World Dredging Congress.* World Dredging Association, Las Vegas, NV.

LaSalle, M. W., Clarke, D. G., Homziak, J., Lunz, J. D., and Fredette, T. J. (1991). "A framework for assessing the need for seasonal restrictions on dredging and disposal operations," Technical Report D-91-1, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lisle, T. E., and Lewis, J. (1992). "Effects of sediment transport on survival of salmonid embryos in a natural stream: A simulation approach," *Canadian Journal of Fisheries and Aquatic Science* 49, 2337-2344.

Lohrman, A., and Huhta, C. (1994). "Plume measurement system (PLUMES) calibration experiment," Technical Report DRP-94-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lotspeich, F. E., and Everest, F. H. (1981). "A new method for reporting and interpreting textural composition of spawning gravel," U.S. Forest Service Research Note PNW-369.

Morgan, J. D., and Levings, C. D. (1989). "Effects of suspended sediments on eggs and larvae of lingcod, Pacific herring, and surf smelt," Canadian Technical Report Fisheries and Aquatic Sciences 1729:I-VII; 1-31.

Nisbet, R. M., Muller, E. B., Lika, K., and Kooijman, S.A.L.M. (2000). "From molecules to ecosystems through dynamic energy budget models," *Journal of Animal Ecology* 69, 913-926.

Noonburg, E. G., Nisbet, R. M., McCauley, E., Gurney, W. S. C., Murdoch, W. W., and de Roos, A. M. (1998). "Experimental testing of dynamic energy budget models," *Functional Ecology* 12, 211-222.

Puckette, T. P. (1998). "Evaluation of dredged material plumes — Physical monitoring techniques," *DOER Technical Notes Collection* (TN DOER-E5), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *http://el.erdc.usace.army.mil/dots/doer/doer.html*

Reine, K. J., Clarke, D. G., and Dickerson, C. (2002). "Acoustic characterization of suspended sediment plumes resulting from barge overflow," *DOER Technical Notes Collection* (ERDC TN-DOER-E15), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *http://el.erdc.usace.army.mil/dots/doer/doer.html*

Richards, A. F., Hirst, T. J., and Parks, J. M. (1974). "Bulk density-water content relationship in marine silts and clays," *Journal of Sedimentary Petrology* 44, 1004-1009.

Sabelman, E. E, Jaffe, D. L., Kenney, D. E., Troy, B. S., and Yap, R. "Accelerometric upper body motion analysis for diagnosis and therapy of mobility disorders," in preparation, *Journal of Rehailitation Research and Development.*

Stacey, N. E., and Hourston, A. S. (1982). "Spawning and feeding behavior of captive Pacific herring, *Clupea harengus pallasi,*" *Canadian Journal of Fisheries and Aquatic Sciences* 39, 49-498.

Terrados, J., Duarte, C. M., Fortes, M. D., Borum, J., Agawin, N. S. R., Bach, S., Thampanya, U., Kamp-Nielsen, L., Kenworthy, W. J., Geertz-Hansen, O., and Vermaat, J. (1998). "Changes in community structure and biomass of seagrass communities along gradients of siltation in SE Asia," *Estuarine and Coastal Shelf Science* 46, 757-768.

Thomas, S., and Ridd, P.V. (2004). "Review of methods to measure short time scale sediment accumulation," *Marine Geology* 207, 95-114.

Tubman, M. W., and Corson, W. D. (2000). "Acoustic monitoring of dredging-related suspended-sediment plumes," *DOER Technical Notes Collection* (ERDC TN-DOER-E7), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *http://el.erdc.usace.army.mil/dots/doer/doer.html*

Tubman, M. W. (1995). "Plume measurement system (PLUMES) technical manual and data analysis project," Technical Report DRP-95-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Tubman, M., Brumley, B., and Puckette, P. T. (1994). "Deep-water dredged-material disposal monitoring offshore of San Francisco using the PLUme MEasurement System (PLUMES)." *Dredging '94, Proceedings of the second international conference on dredging and dredged material placement, Lake Buena Vista, Florida.*

U.S. Environmental Protection Agency and U.S. Army Corps of Engineers. (1991). "Evaluation of dredged material proposed for ocean disposal (Testing manual)," Office of Water (WH-556F), EPA-503/8-91/001, prepared under EPA Contract 68-C8-0105. February, 1991.

Waters, T. F. (1995). "Sediment in streams – sources, biological effects and control," American Fisheries Society Monograph 7. American Fisheries Society, Bethesda, MD.

Wilber, D.H., and Clarke, D.G. (2001). "Biological effects of suspended sediments: A review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries," *North American Journal of Fisheries Management* 21, 855-875.

Wilber, D. H., Clarke, D. G., Brostoff, W. and Ray, G. L. "Sedimentation: Potential biological effects from dredging operations in estuarine and marine environments," in preparation. U. S. Army Engineer Research and Development Center, Vicksburg, MS.